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# A 16-beam Non-Scanning Swath Mapping Laser Altimeter Instrument

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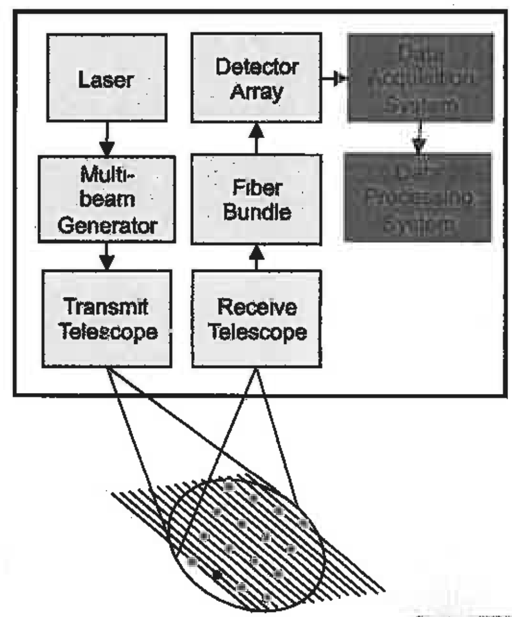
# Instrument Incubator Program (IIP) Objectives and Approaches



**Objectives –**

- Develop key technologies to meet the LIST mission requirements and provide scalability study for spaceborne mission.
- Advance TRL of critical subsystems (Laser & Detector) on airborne platform.
- Develop and demonstrate a >15% wall plug efficient laser system coupled with a highly sensitive detector array to realizing the global elevation mapping goals of the LIST mission.




**Approaches –**

- Develop and demonstrate a 16-channel airborne instrument – ***Airborne Lidar Surface Topography Simulator (ALISTS)*** to demonstrate key subsystems and measurement techniques in support of the LIST mission.
- Key subsystems being matured in this IIP – Laser, Detectors and Optical System.
- COTS – Data Acquisition and Processing Systems

# LIST Mission Objectives and Requirements

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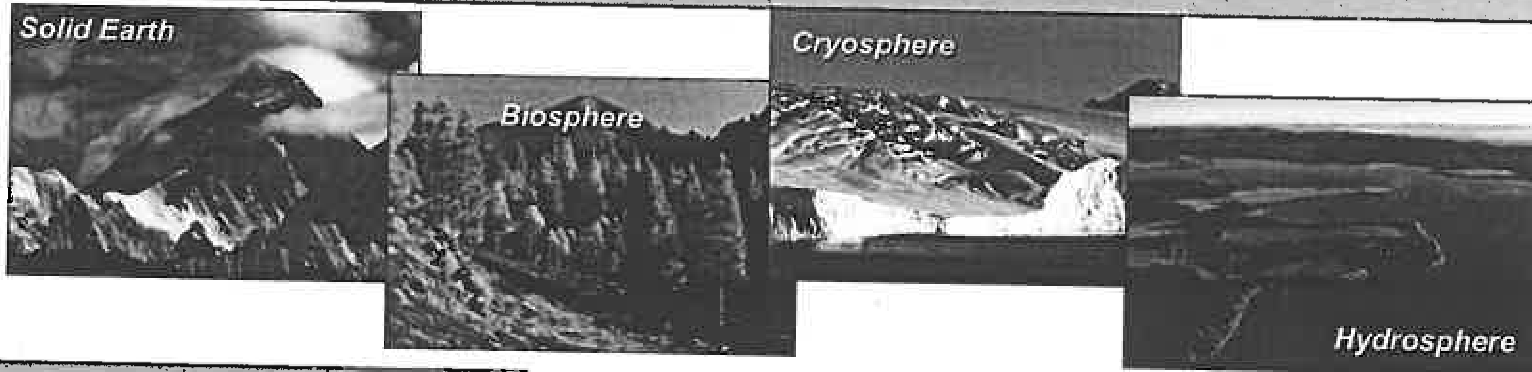
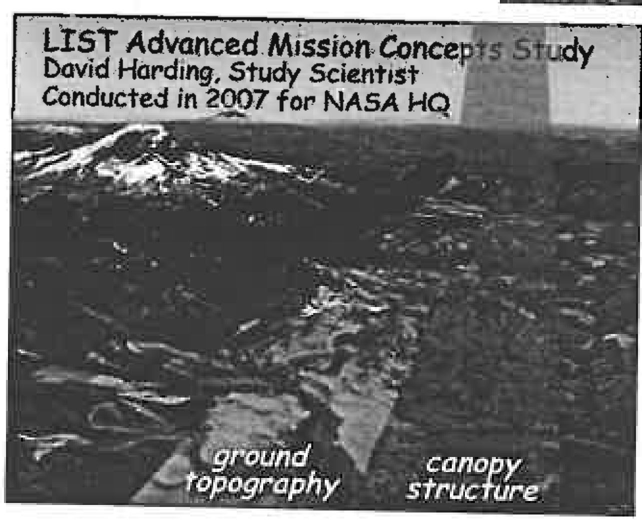
***The Lidar Surface Topography mission will serve a diverse array of science and applications objectives, providing foundation data on the Earth's topography, the height of overlying covers of vegetation, water, snow and ice, and their change.***




- **Map land topography including where covered by dense vegetation**
  - 5 m spatial resolution
  - 10 cm vertical precision
  - 20 cm absolute elevation accuracy
- **Map vegetation height and vertical structure**
  - 1 m accuracy for 25 m x 25 m area
- **Complete global mapping in 3 years**
  - 5 km swath to build up coverage during clear sky conditions
  - Multi-beam "push-broom" approach: 5 km / 5 m = 1,000 beams
  - ***Requires highly efficient measurement approach***

***ALISTS measurement approach developed to meet the demanding LIST requirements***

# ALISTS Spaceflight LIDAR Mission Context

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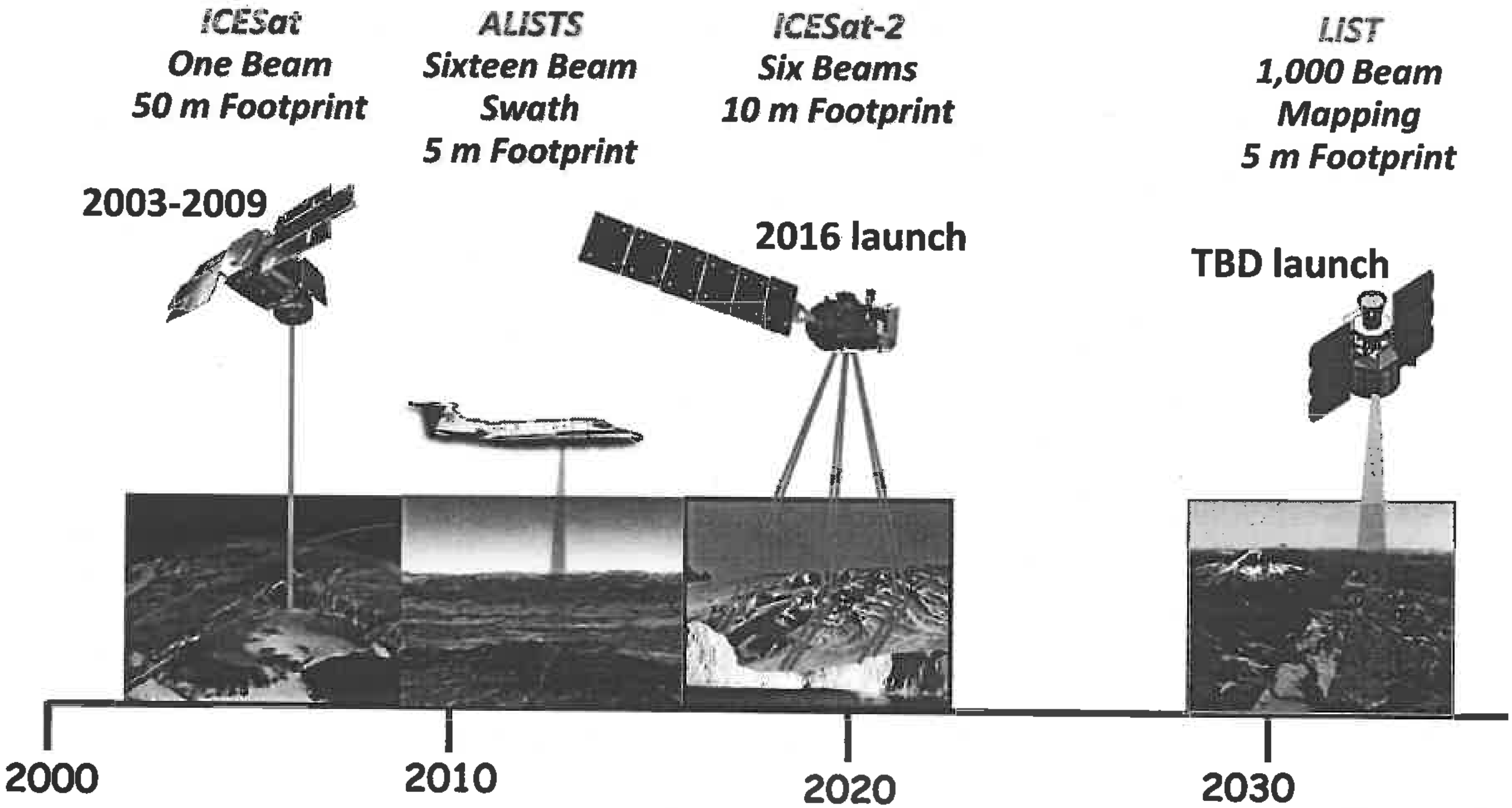

# ALISTS and LIST: An Efficient Lidar Measurement Approach

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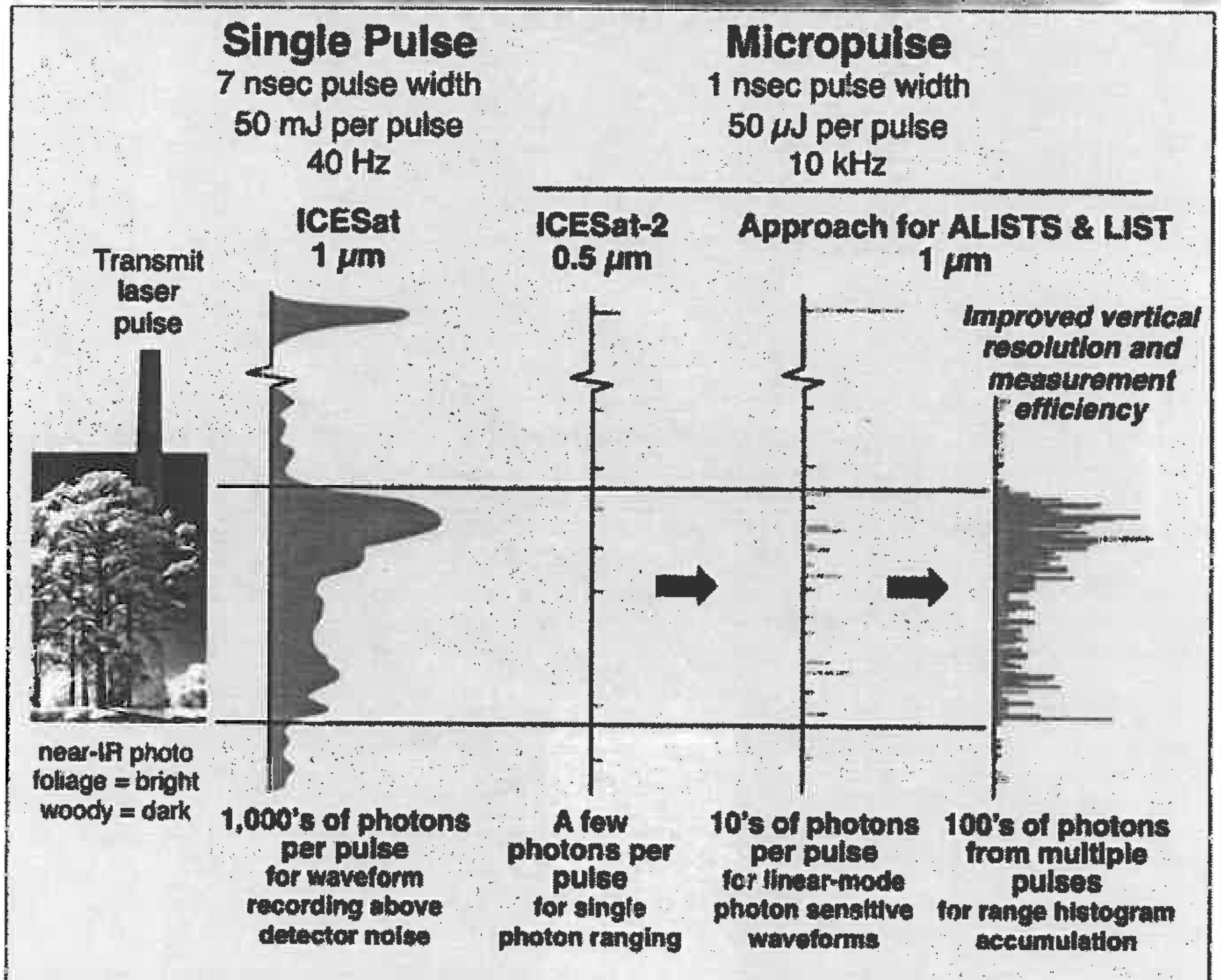




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# Key differences between LIST lidar and earlier lidars



- Laser Transmitters:
  - Low to medium pulse energy and high pulse rate, similar to ICESat-2/ATLAS but at a near IR wavelength
  - Much higher electrical to optical conversion efficiency
- Optics and Alignment
  - Similar to previous lidars but with up to 1000 instantaneous field of view (IFOV), or pixels, and new challenges in alignment
- Detectors:
  - Infrared, single-photon-sensitivity, linear-mode analog output, and multiple element array
- Signal Processing
  - On board storage, filtering, and data volume reduction

# IIP ALISTS Instrument Concept & Performance Prediction

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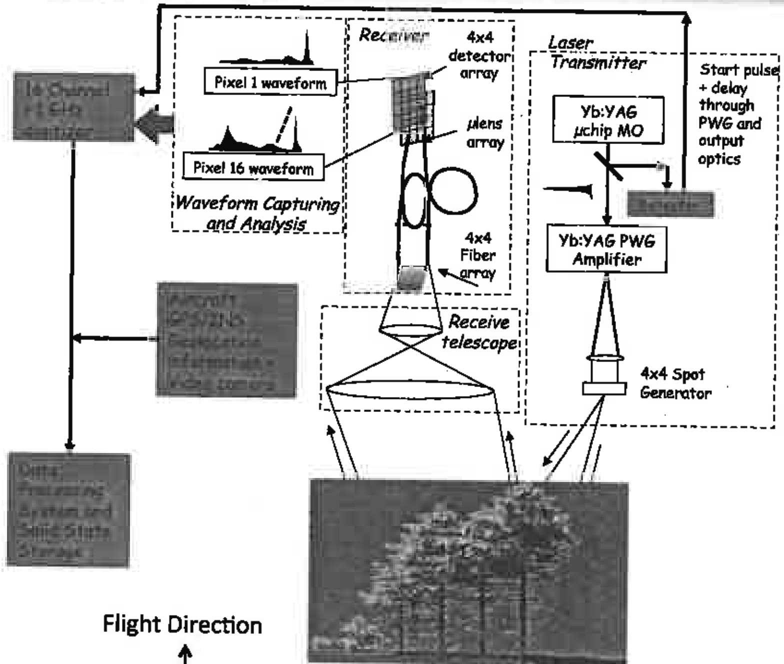
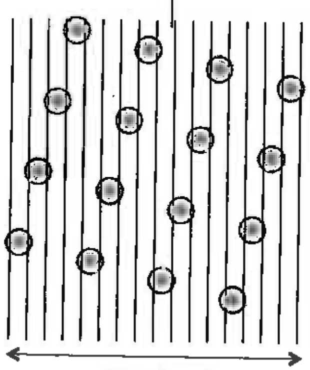
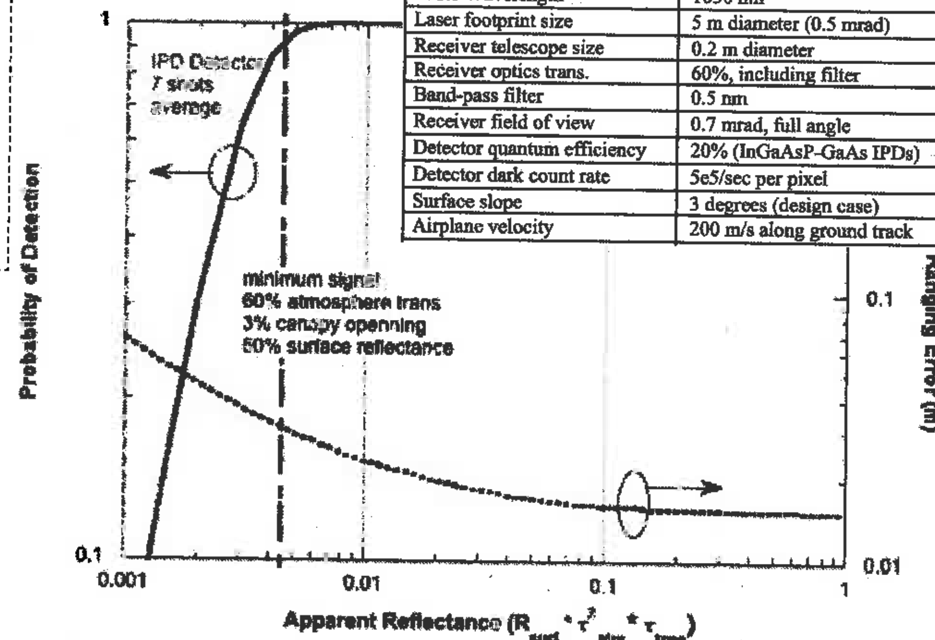



| | |
|---|---|
| Orbit altitude | 10 km |
| Local sun elevation angle | 0-10 degrees |
| Laser pulse energy | 5.5 uJ, 16 beam |
| Laser pulse rate | 2 kHz |
| Laser pulse width | 1 ns FWHM |
| Laser Wavelength | 1030 nm |
| Laser footprint size | 5 m diameter (0.5 mrad) |
| Receiver telescope size | 0.2 m diameter |
| Receiver optics trans. | 60%, including filter |
| Band-pass filter | 0.5 nm |
| Receiver field of view | 0.7 mrad, full angle |
| Detector quantum efficiency | 20% (InGaAsP-GaAs IPDs) |
| Detector dark count rate | 5e5/sec per pixel |
| Surface slope | 3 degrees (design case) |
| Airplane velocity | 200 m/s along ground track |




Altitude = 10 km
16 adjacent, parallel beams
Detector FOV = 7 m (0.7 mrad);
Laser Spot = 5 m (0.5 mrad);
Spot Spacing = 20 m (2 mrad)




- Same approach as for space, with:
  - Lower altitude: 10 vs 400 km
  - Smaller telescope: 0.2 vs 2 m
  - Lower laser energy: 5 vs 50 μJ
- Significant over sampling along track at lower aircraft velocity:
  - Allows optimization of measurement & signal processing techniques.

# Spaceflight and Airborne Measurement Comparisons

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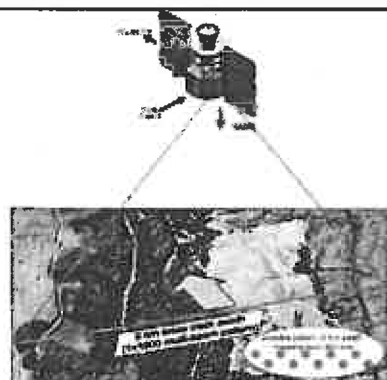
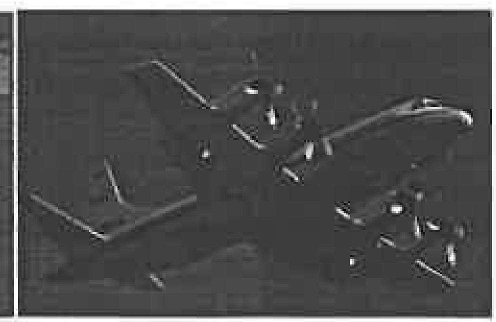
**All use micropulse lidar with waveform capturing and analysis detection scheme**

| Parameters | Spaceborne Instrument | Airborne Instrument Engineering Flights | Airborne Instrument Science Demonstration Flights |
|---|---|---|---|
| Spatial Resolution | 5 meter | 5 meter | 5 meter |
| Beam Divergence | 12.5 μrad | 0.5 mrad | 0.5 mrad |
| Altitude | 400 km | 32.8 kft / 10 km | ~28 kft / ~8 km |
| Swath Width | 5 km | 80 m | 80 m |
| Laser Energy | 50 μJ/beam for 1000 beams @ 10 kHz* | ~5 μJ/beam for 16 beams @ 2 kHz | ~5 μJ/beam for 16 beam @ 10 kHz |
| Detector (> 1 GHz bandwidth/pixel) | 1000 pixels | 16 pixels | 16 pixels |
| Platform Speed | 7000 m/sec | 200 m/sec | ~170 m/sec |
| Number of footprints per 5-m along track | 7 | 50 | 300 |





*assuming detector similar to Intevac IPD performance for spaceborne mission

# ALISTS Airborne Campaigns

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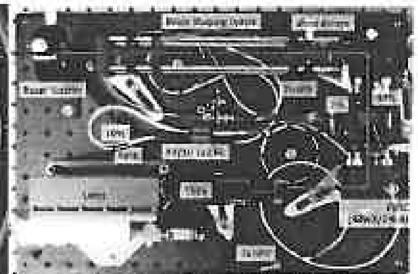
**Engineering Flights – Sept 2011**
- Platform: Lear-25
- Location: NASA GRC
- Laser: Microchip Laser
- Detector: Intevac 16 element IPD
- Number of beams: 16
- Altitude: 10 km

**Science Demonstration Flights – Aug 2012**
- Platform: P-3B
- Location: NASA WFF
- Laser: Microchip Laser & MOPA Laser
- Detector: Intevac 16 element IPD
- Number of beams: 16
- Altitude: 1-2 km (due to SNR limitation)




# ALISTS Instrument Overview

***JOHN CAVANAUGH***
*NASA GSFC CODE 554*

# Airborne Instrument Requirements



- **Measure pulse time of flight**
  - 0.1 m accuracy for 1° slopes
  - 0.5 m accuracy for 10° slopes
- **Signal Characteristics**
  - 10 kHz pulse repetition rate
  - 1 transmit pulse
    - 0.7 – 1.0 ns FWHM Gaussian
  - 16 received pulses
    - Signal spreading < 300 m (2 μs max)
- **Detector Bandwidth**
  - Constant group-delay filter
    - 467 MHz -3 dB
    - 1 GHz -50 dB
- **Rx Tracking Requirement**
  - Track 2 μs Rx signal window
    - Center sample window on signal
      - ± 150 m window
    - Adjust at >2 Hz rate (5k shots)
- **Acquisition Requirements**
  - 8-bit quantization (ENOB > 6.5)
  - Sample rate > 1.5 GS/s
  - Data rate for 2 μs Rx window @ 1.5 GS/s:
    3000 samples x 16 channels Rx
    100 samples Tx
    -> 500 MB/s continuous rate
- **Storage Requirement**
  - 1 Hour continuous -> 1.8 TB
- **Ancillary Data**
  - Aircraft Nav Data
  - GPS & Attitude (Applanix)
  - Nadir video stream

# ALISTS Block Diagram & Measurement Pattern

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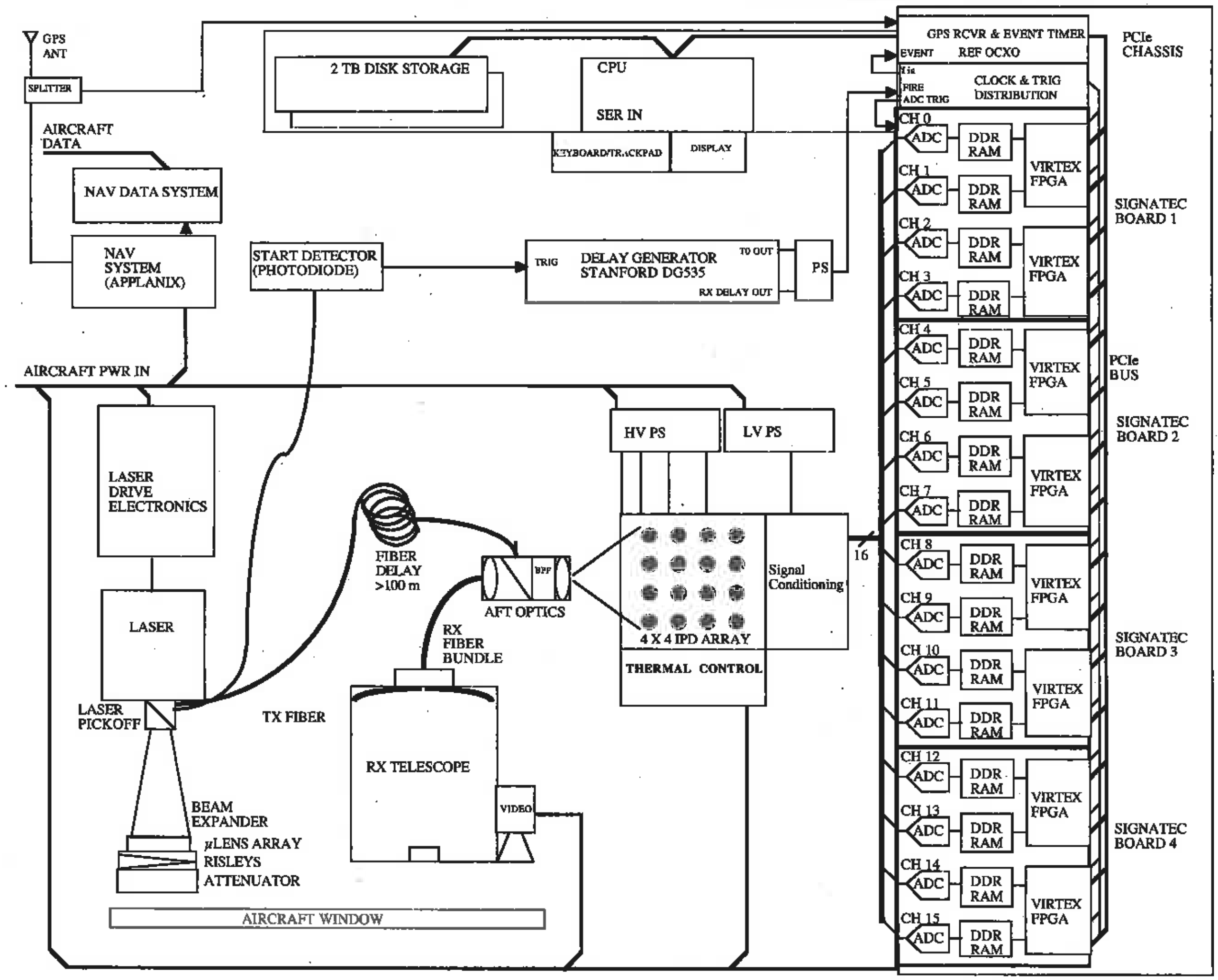
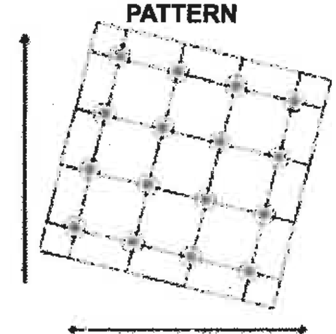


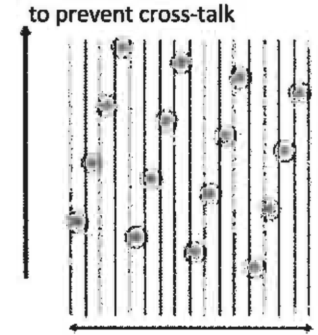

**MEASUREMENT PATTERN**



**Swath Width**

4 x 4 fiber-coupled detector array rotated 14.5°

Detector FOV's separated to prevent cross-talk



16 contiguous, cross-track, 5 m wide profiles in flight direction

At 10 kHz rep rate and 200 m/sec ground speed spots spaced 2 cm along track; 35x oversampling compared to LIST



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# ALISTS Transceiver and Racks for Lear-25 and P3 Flight Campaigns

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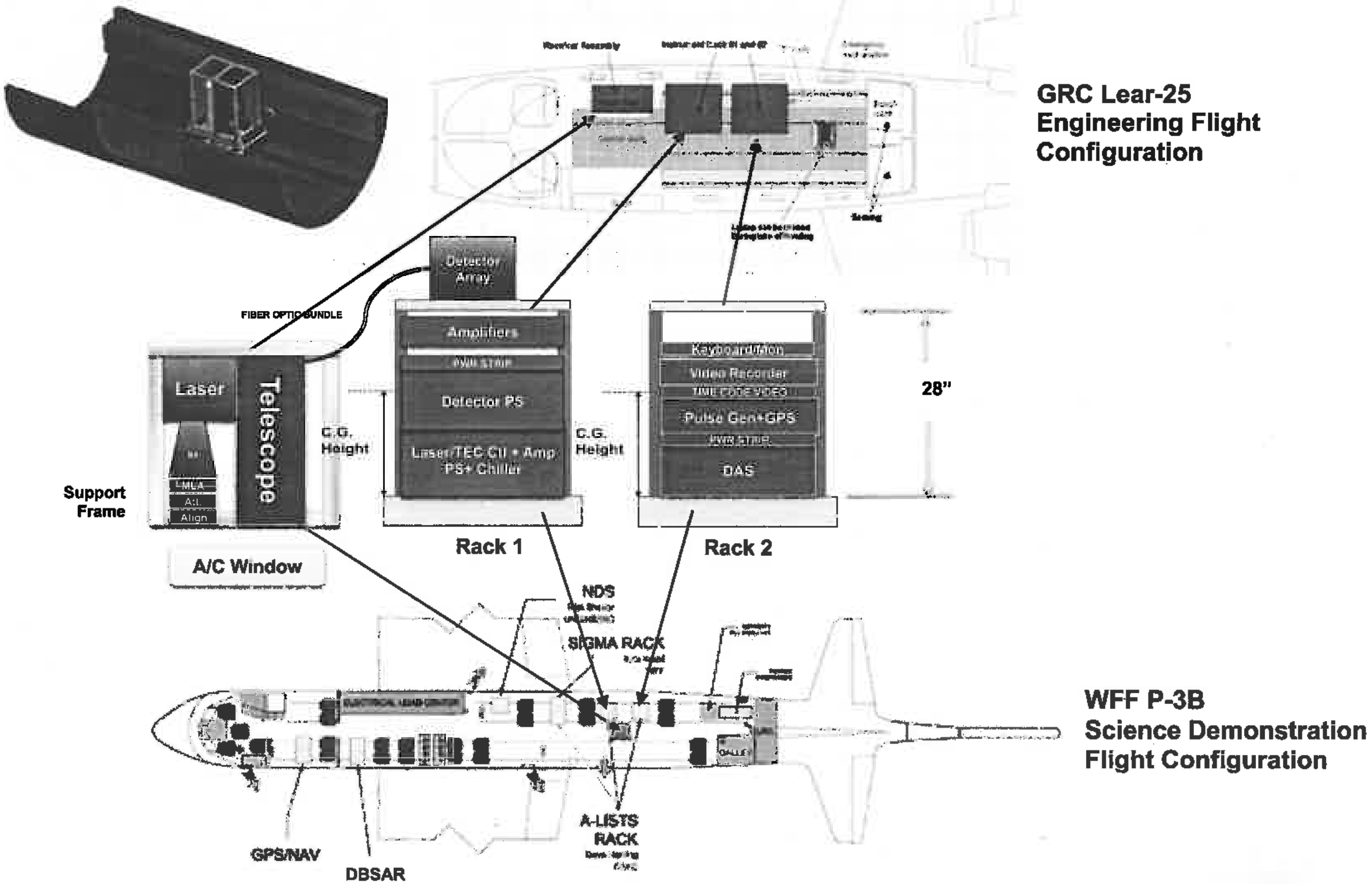

# Yb:YAG Microchip Laser for ALISTS

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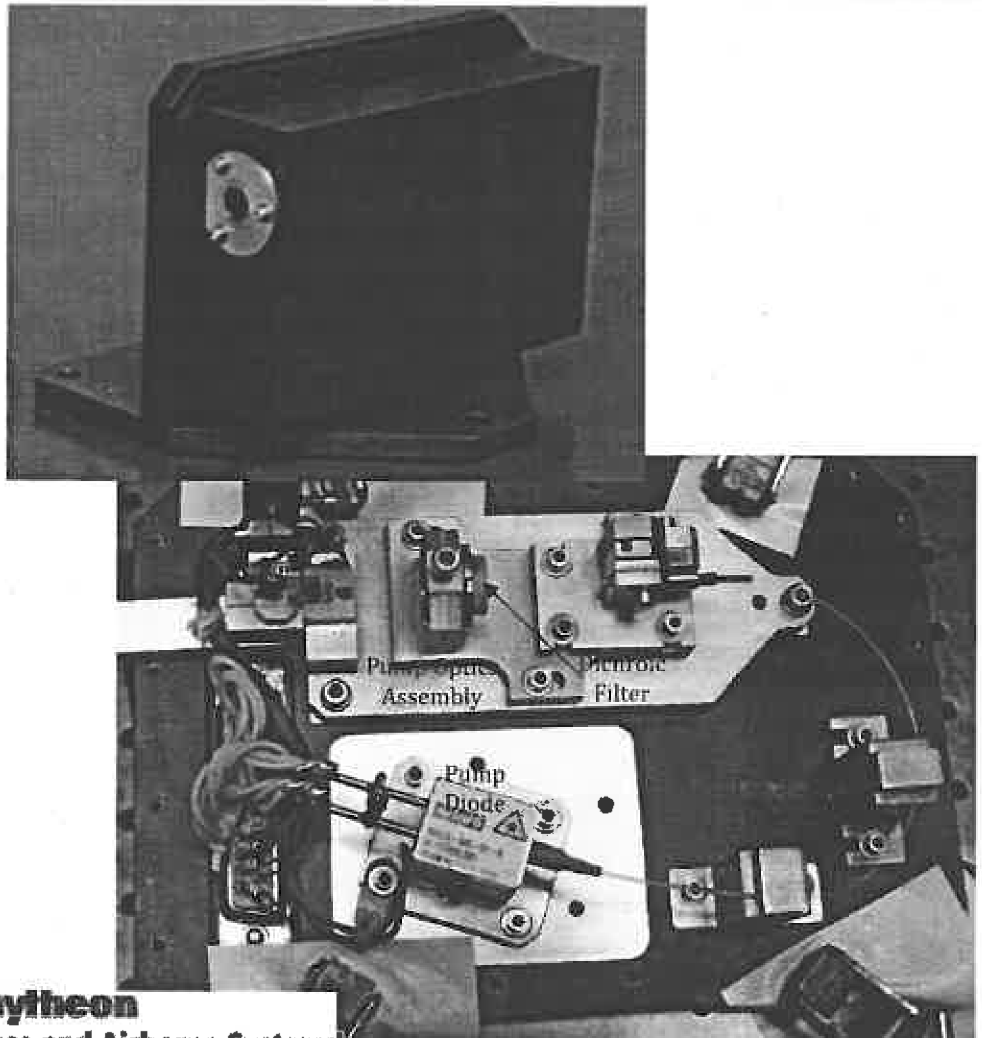


**Laser Output Beam Parameters**

| | |
|---|---|
| Pulse Energy: | 0.1 mJ |
| Repetition Rate: | 10 kHz |
| Wavelength: | 1030.2 nm |
| Linewidth: | 17 pm |
| Polarization Ext: | 25 dB |
| Pulsewidth: | 0.83 nsec |
| Beam Quality M2: | 1.3 |
| O-O Efficiency: | 25% |

**Laser Operating point**

| | |
|---|---|
| Diode Current: | 4.5 A |
| Diode Output Power: | 3.9 W |
| Chiller Temp: | 29.8 $^{0}$C |
| Diode Temp: | 31 $^{0}$C |
| $\mu$Chip Temp: | 17.8 $^{0}$C |
| VBG Temp: | 20 $^{0}$C |

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# Packaged MOPA for Swath Mapper IIP – Power Scaling Demonstration

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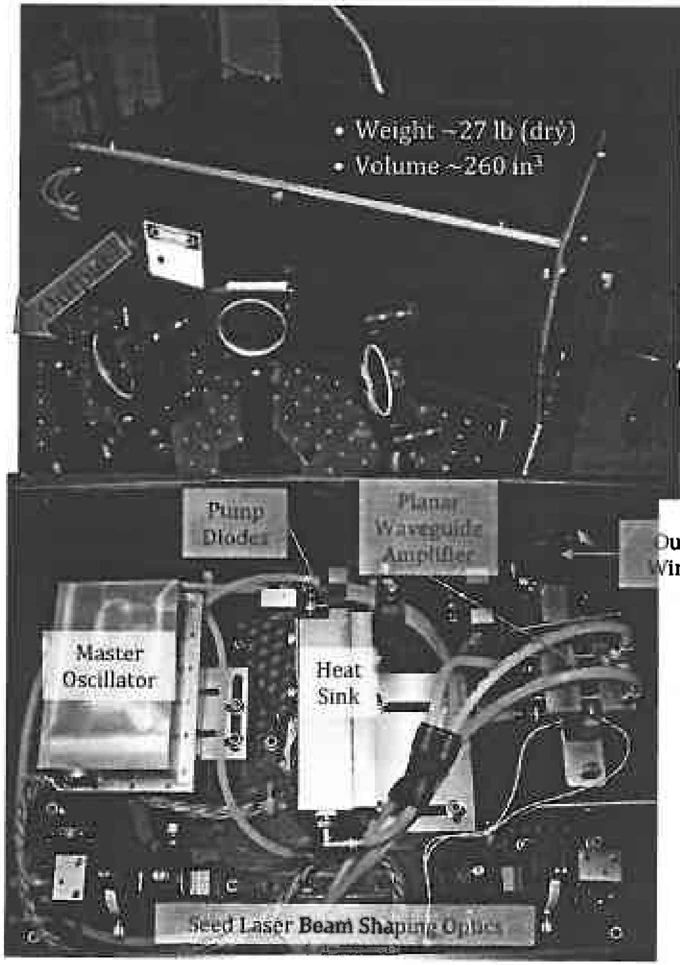
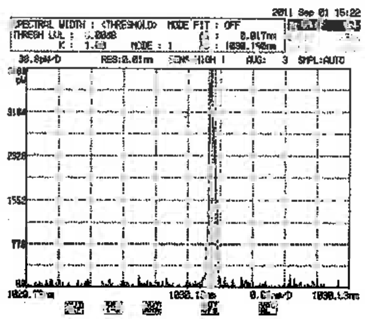
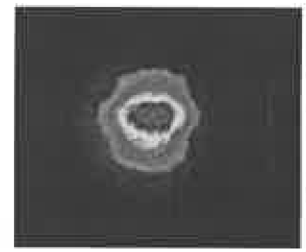
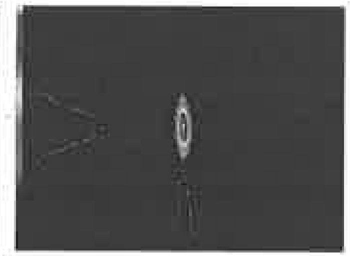


Wavelength ~1030.2 nm; <20 pm spectral width



NF Image at ~84 cm from MOPA Output
FW1/$e^2$ size: 2.6 mm x 3.3 mm



FF Image

## MO Nominal Operating Point

| | |
|---|---|
| • Pulse Energy | 0.1 mJ |
| • Repetition Rate | 10 kHz |
| • Wavelength | 1030.2 nm |
| • Linewidth | 0.018 nm |
| • Polarization ER | 25 dB |
| • Pulsewidth | 0.8 nsec |
| • Beam Quality | $M^2$ ~1.3 |
| • Opt-Opt Efficiency | 25.6% |
| • El-Opt Efficiency | 12.8% |

## MOPA Nominal Operating Point

| | |
|---|---|
| • Pulse Energy | 2.2 mJ |
| • Repetition Rate | 10 kHz |
| • Wavelength | 1030.2 nm |
| • Linewidth | 0.02 nm |
| • Polarization ER | 18 dB |
| • Pulsewidth | 0.8 nsec |
| • Beam Quality | $M^2$~1.1 |
| • Opt-Opt Efficiency | 24% |
| • El-Opt Efficiency | 11% |

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# Receiver for ALISTS

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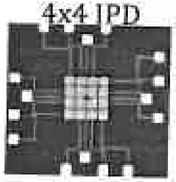
**Selected the Intevac InGaAsP 4x4 intensified photodiode (IPD)**

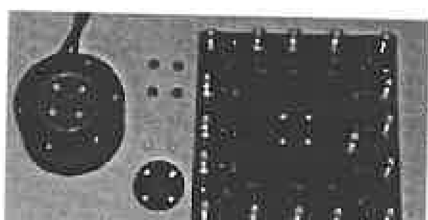
High performance, large active area (mm), high bandwidth (~1GHz), high gain (>10,000), high quantum efficiency (>20%)

InGaAsP field assisted photocathode with QE up to 25% over 950-1300 nm

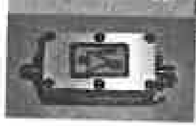
4x4 IPD



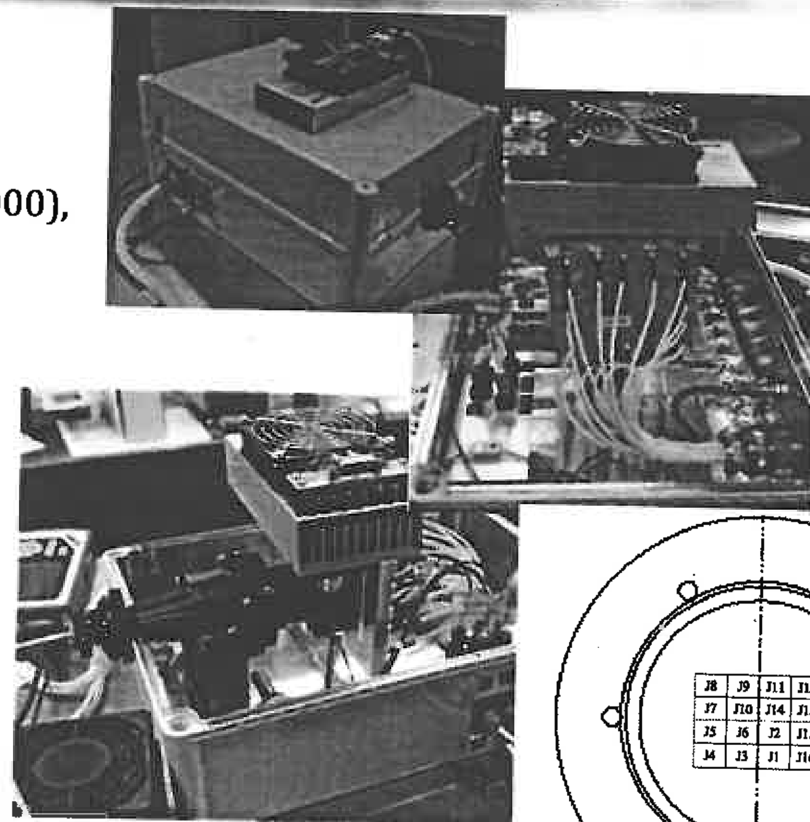
Segmented GaAs APD anodes to form a 4x4 array

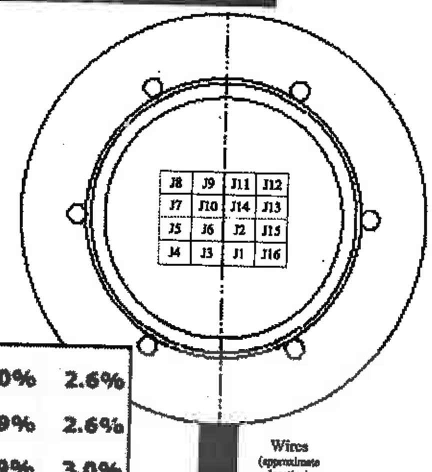


4x4 fan-out at the back of the IPD



Commercial low noise amplifier






| | | | |
|---|---|---|---|
| 2.9% | 2.6% | 1.0% | 2.6% |
| 3.1% | 3.0% | 2.9% | 2.6% |
| 3.1% | 3.2% | 2.9% | 3.0% |
| 3.1% | 3.2% | 2.9% | 2.9% |

QE Map

# ALISTS on Airborne Platforms

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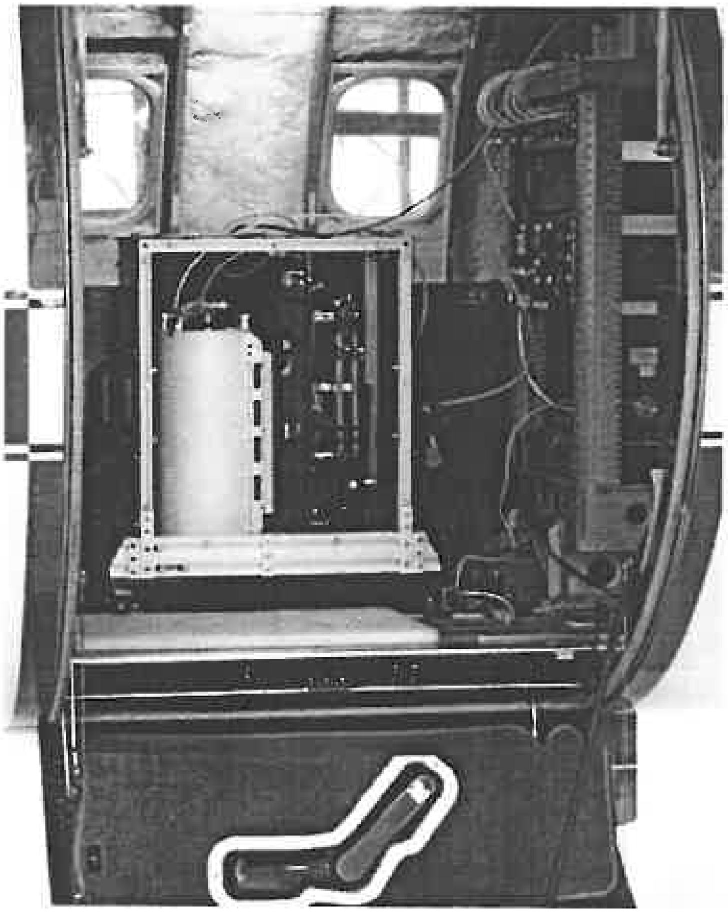
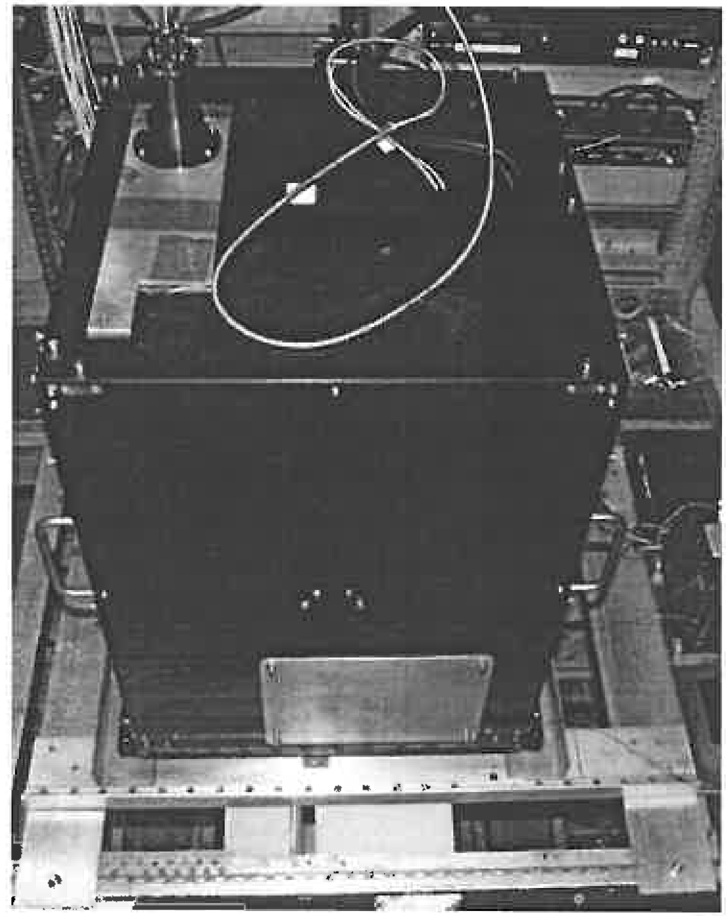
**ALISTS on Lear-25 over Nadir Port 9/2011**



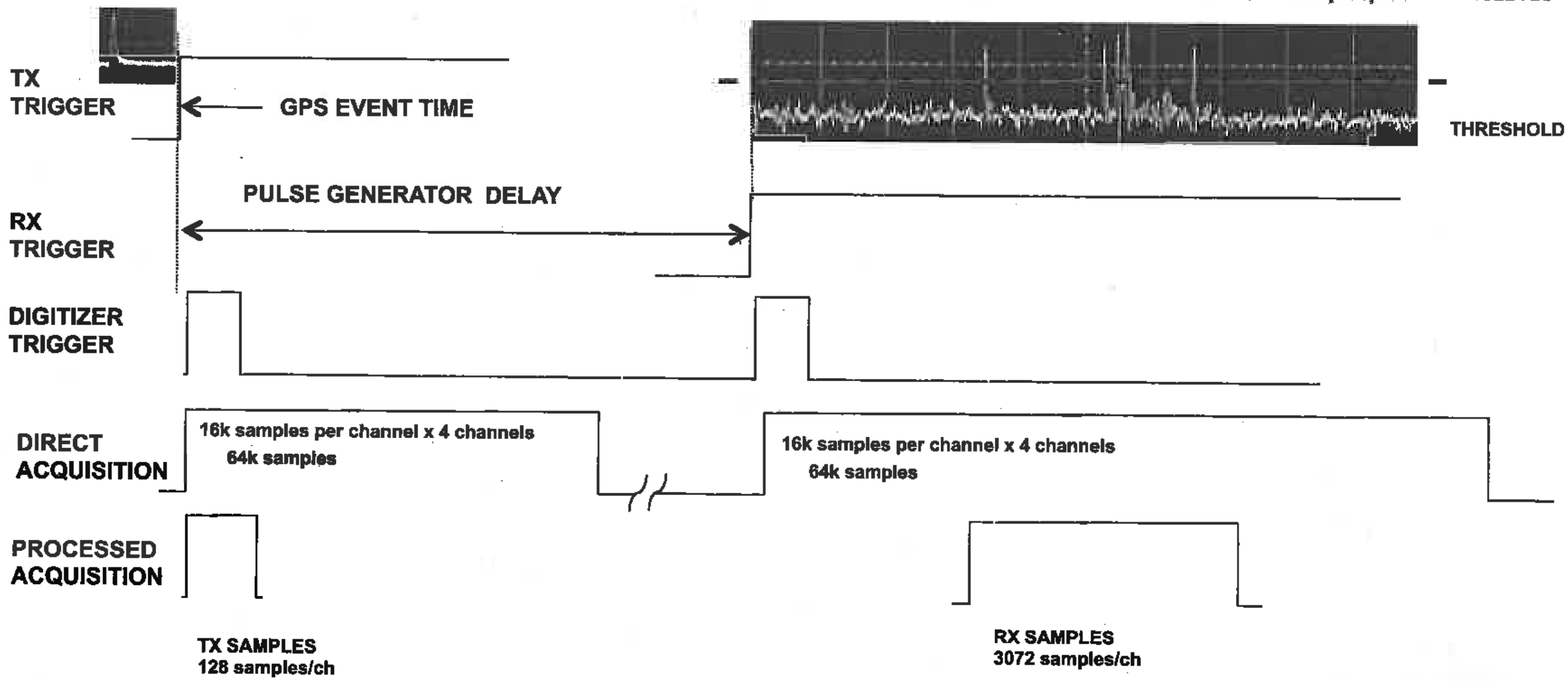
**ALISTS on P-3B over Nadir Port #2 8/2012**



# Signal Acquisition Cycle and Data Rates

- Two acquisition modes for August, 2012 flights:
  - Direct (raw): Rx only, 819 meter range gate, 5-kHz rate
  - Processed (FPGA): Tx+Rx, 1638-meter range gate, 10-kHz rate

| Acquisition Scheme | Laser PRF | Sample rate | TX window samples | RX Window samples | meters | Sample size (bits) | Sample size (bytes) | Channels | Data rate (bytes/s) | 2-hour storage |
|---|---|---|---|---|---|---|---|---|---|---|
| Direct Acquisition | 5000 | 1.50E+09 | 0 | 8192 | 8.E+02 | 8 | 1 | 16 | 655,360,000 | 4.72E+12 |
| Processed Acquisition | 10000 | 1.50E+09 | 128 | 3072 | 3.E+02 | 8 | 1 | 16 | 512,000,000 | 1.02E+10 |



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# Flight Data Collection, Analysis and Validation

***DAVID HARDING AND SUSAN VALETT***
*NASA GSFC CODE 698 & 587*

# September, 2011 Engineering Flights

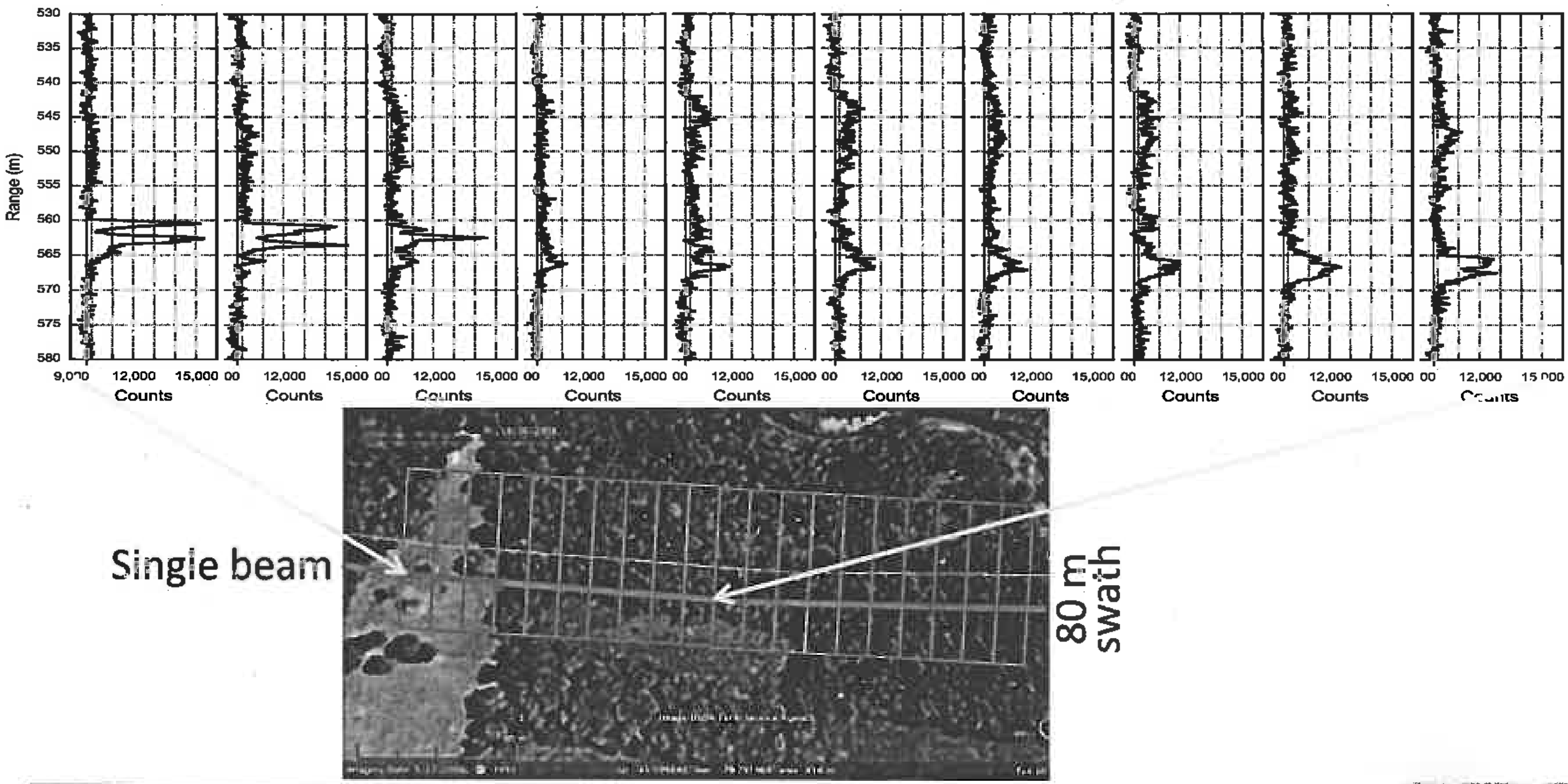


- ***Objectives***
  - Implement measurement approach using master oscillator laser
  - Acquire waveforms over a variety of land cover and terrain types
  - Repeat at multiple altitudes up to 10 km to evaluate link margin model
  - Develop data processing, visualization and analysis software

**The majority of the objectives were met despite limited data collection opportunities, due to slow-moving east coast "frankenstorm" and laser failure due to over current.**

# Land Cover Vertical Structure from ALISTS Waveforms

- Waveforms acquired from 10 km altitude
- 200 laser shot average over 20 m along-track distance
- Vertical structure is consistent with video-documented land cover



# Evaluation of Signal Link Margin Model

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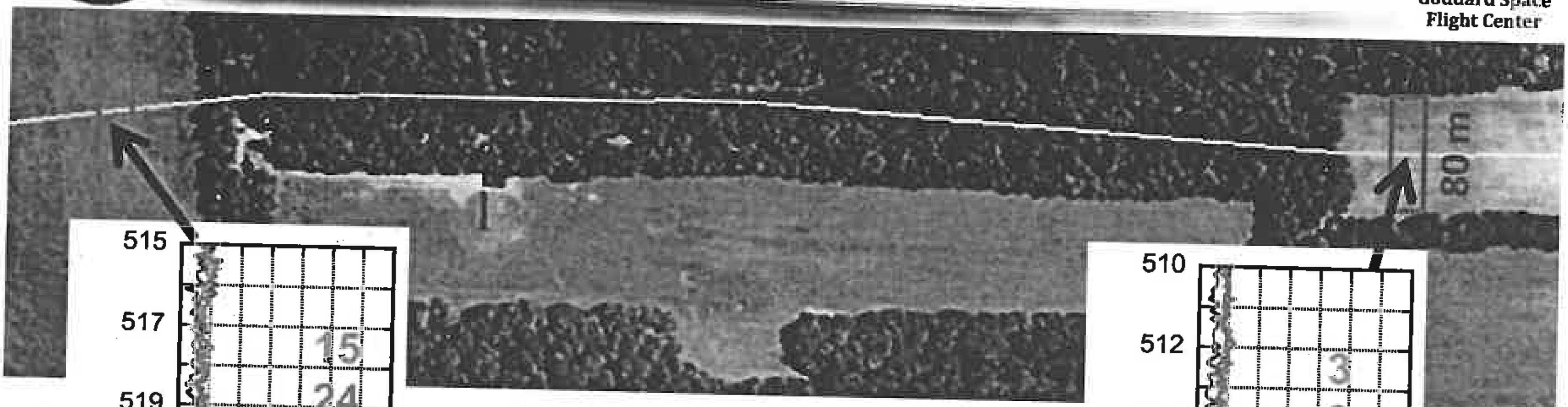
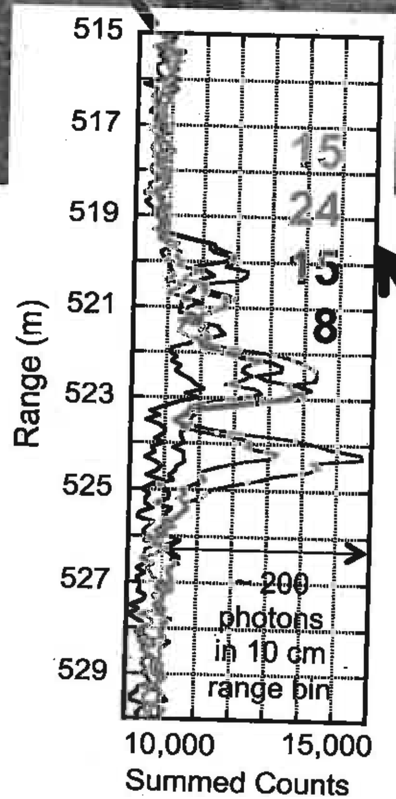



200 shot aggregate waveforms

~ 30 digitizer counts = 1 photon

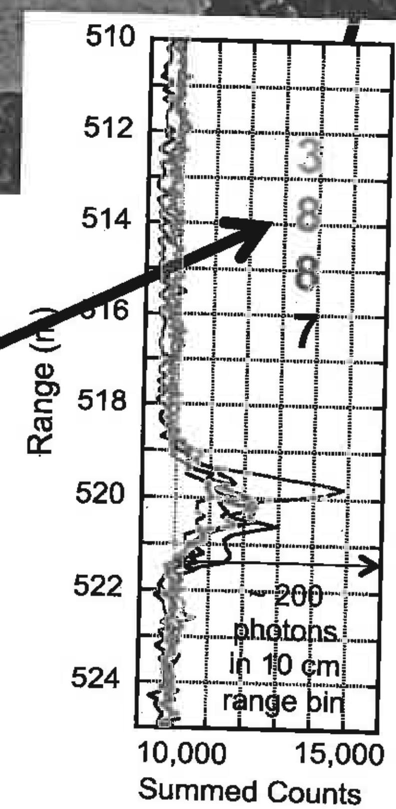
Average number of photons per laser shot per beam

Nominally 10 photons per shot

ALISTS 3% QE detector = 1/5 LIST 15% QE goal

10 photons x 5 x 7 shots/5 m pixel = 350 signal photons

(~1.5x predicted LIST performance)



# August, 2012 Science Demonstration Flights

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- ***Objectives***
  - Acquire data at 10 km for several ecosystem research sites
  - Validate measurement approach by comparison to independent data
  - Utilize master oscillator power amplifier laser in-flight

**Validation accomplished although flights had to be conducted at 1.5 km to overcome signal loss due to instrument misalignment and low window transmission and wavefront distortion**

ALISTS August, 2012 flight over Wallops Flight Facility
Repeated SIMPL August, 20011 lines: yellow
Crossed G-LiHT high-res lidar mapping: white outline
Targeted field stem map plots: red dots
ALISTS and SIMPL comparison: red line

# ALISTS Waveforms and SIMPL Single Photons

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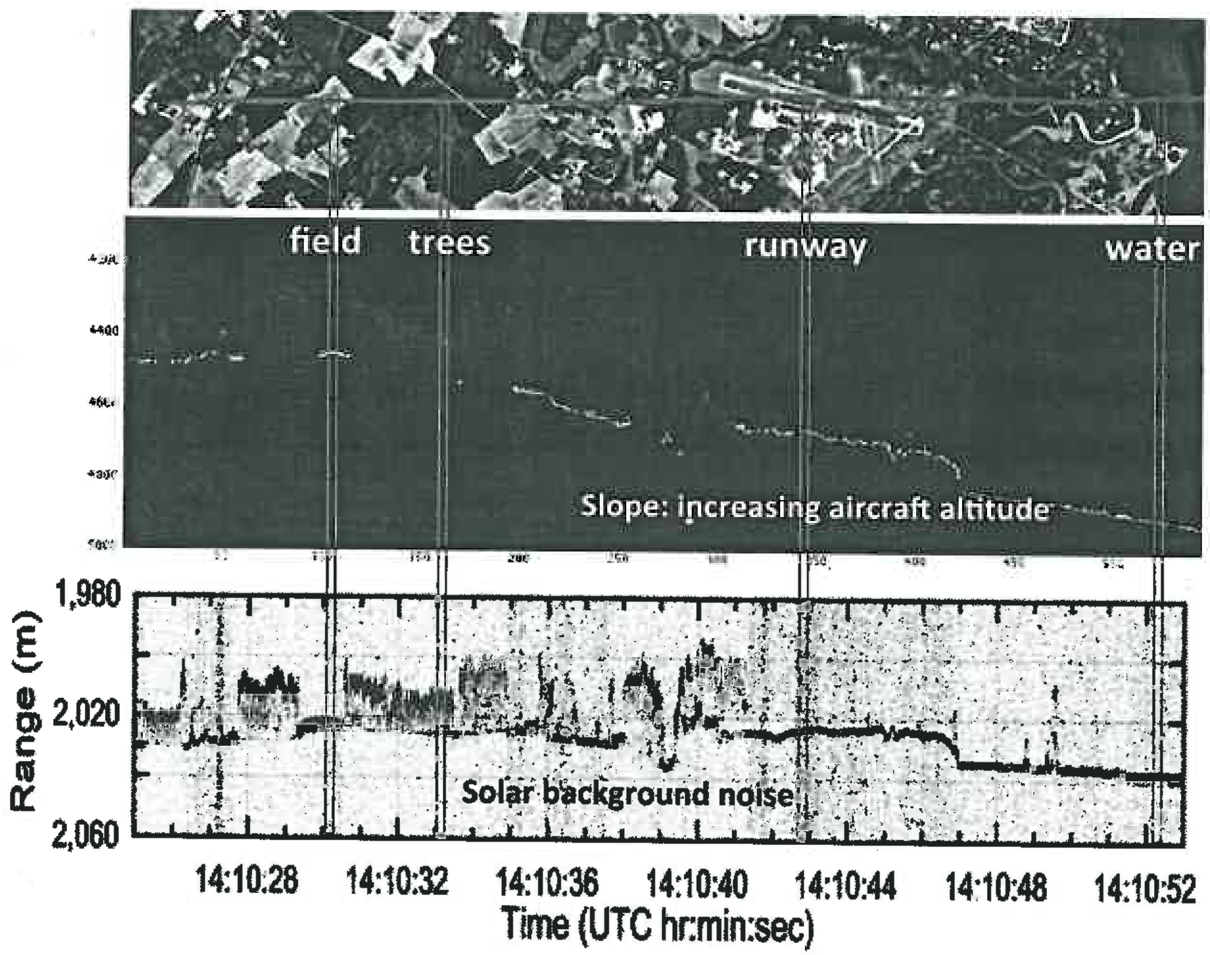


ALISTS 8/29/12
and SIMPL 8/23/11
flight track (red)

**ALISTS**
Waveforms
1,000 shot averages
Color = amplitude

**SIMPL**
Single photons
High sampling density
provides validation data

# Wallops Runway Results: Flat Surface Returns

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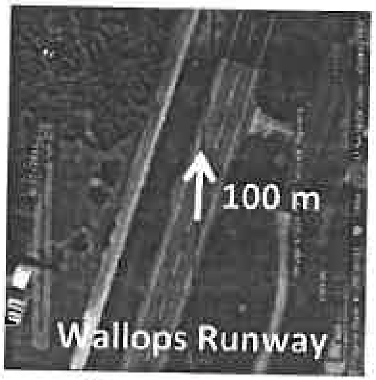
### SIMPL Histogram

One 532 nm beam of 4
0.2 footprints
Single photon detection
10 cm range bins
~10,000 laser shots
~20% PD
~ 100 m along-track distance

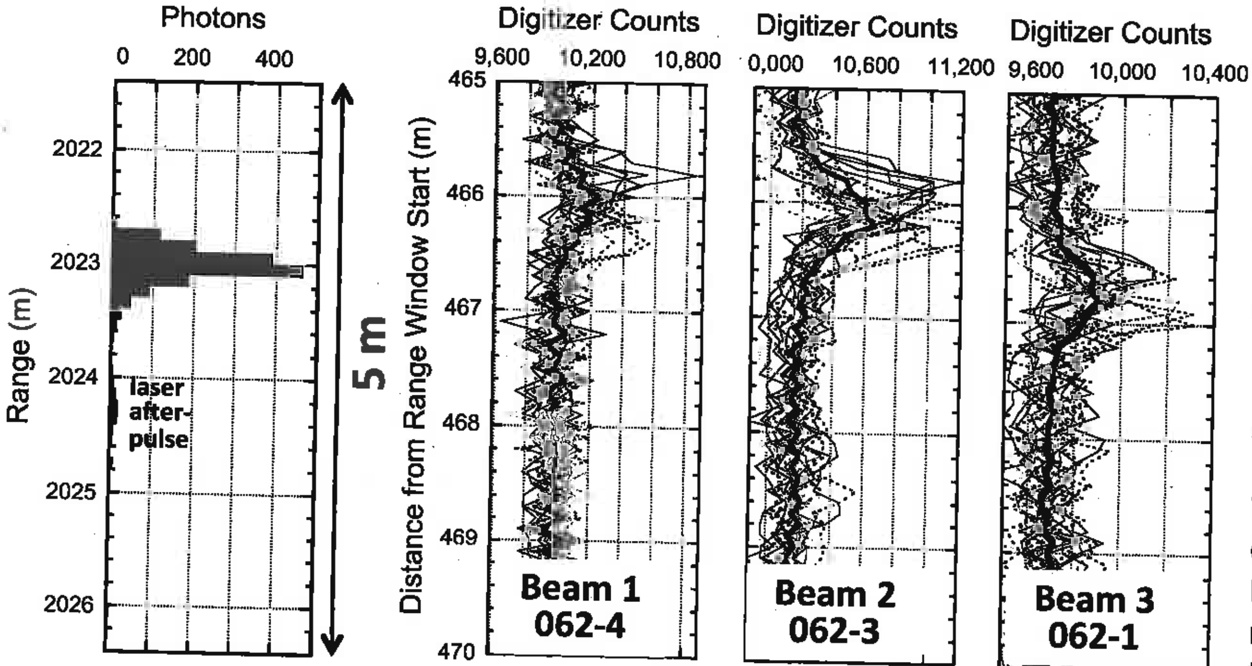



### *SIMPL & ALISTS narrow width returns*

Similar ~20 cm FWHM impulse responses
Due to short pulses and high timing resolution

### *10 cm range precision*

shown for ALISTS by within-beam range change of 5 m along-track waveforms across runway




### ALISTS Waveforms

Three 1064 nm beams of 16
0.7 m footprints
Linear-mode photon detection
1.5 GHz digitization
10 cm range resolution
19 along track waveforms plotted
Each combining 215 laser shots
~ 5 m along-track distance
Average waveform (bold black)
~ 100 m along-track distance
Waveform offsets between beams due to channel timing biases
Low SNR due to receiver misalignment and low window transmission



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# Waveform Validation for Several Surface Types

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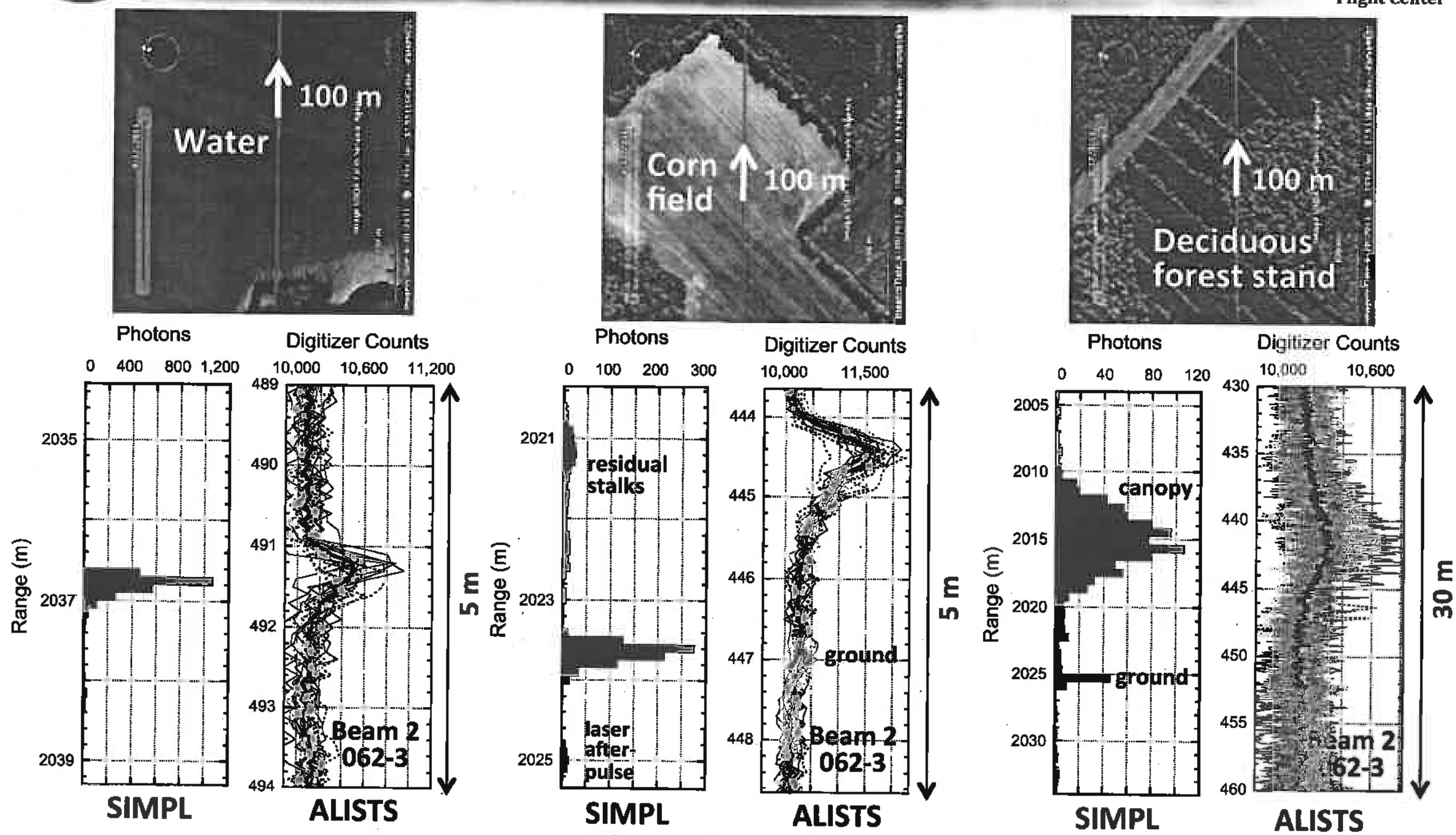


post-harvest pre-harvest

field conditions from in-flight nadir videos

# Consistent Waveforms Across the 16 Beam Swath

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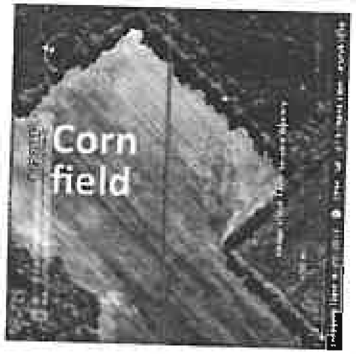
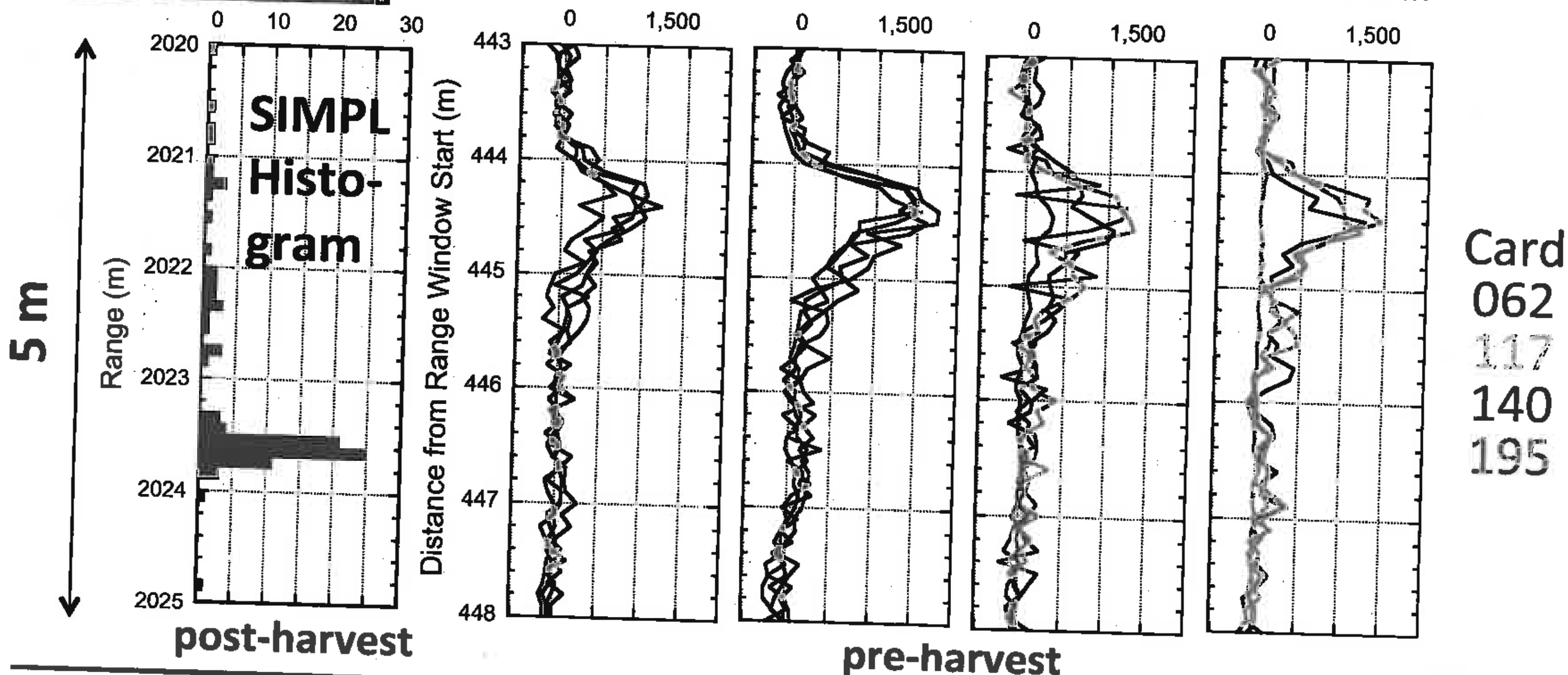



## ALISTS Waveforms

- Sixteen cross-track beams plotted in groups of 4 adjacent beams
- Each waveform combines 215 laser shots over ~5 m distance
- Noise floors and range biases removed
- Show systematically changing structure across the swath
- Indicates the absence of optical and electronic cross-talk



# Conclusion

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*NASA GSFC CODE 554 AND 698*

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# IIP Accomplishments

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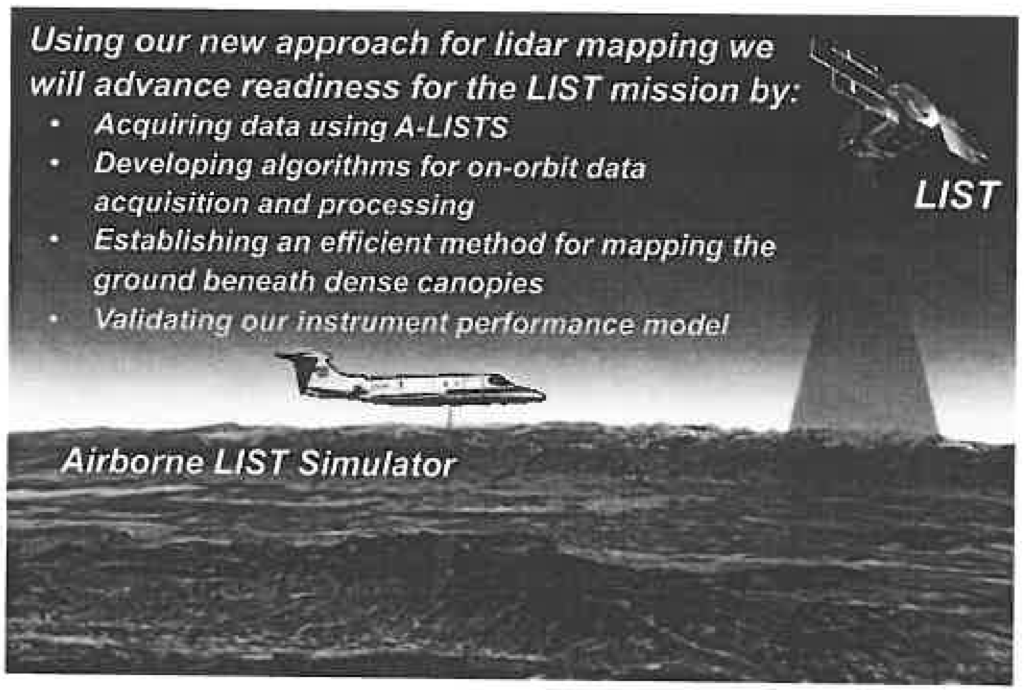
1. **Developed and demonstrated a highly efficient measurement approach that can meet the LIST mission requirements**
    a. Micropulse, photon-sensitive waveform recording using multi-beam, swath-mapping;
    b. Modeled performance to define instrument and sub-system requirements.
2. **Working with vendor partners, advanced laser and detector technologies needed to achieve the performance requirements**
    a. Short pulse (< 1 ns) multi-beam laser transmitters with >12% wall plug efficiency:
        a. Master Oscillator used in airborne flights
        b. Master Oscillator Power Amplifier demonstrating power scaling for spaceflight
    b. High sensitivity, linear mode array detectors for photon sensitive waveform capturing;
    c. Characterized performance of key new components/technologies in the lab and in flight.
3. **Designed, assembled, flight tested, and evaluated the Airborne List Simulator, a prototype swath mapping instrument**
    a. 4x4 laser array and 4x4 receiver array for a 16-channel LIST prototype;
    b. Same spatial resolution (5-m spot diameters) as LIST;
    c. Demonstrated and validated measurements over a variety of surface types, including those of vegetation canopy and underlying topography.
4. **Advanced technical readiness of a scalable instrument architecture for LIST**

> Accomplished goals: Developed and demonstrated a highly efficient measurement approach and worked with vendor partners to mature the needed laser and detector technologies.

# Follow-on Science Plans

Goddard Space Flight Center

- ***3 Year Space Geodesy ROSES-2010 Project***
  - "Algorithm Development and Observation Strategies for the LIST Geodetic Imaging Mission"
  - Acquire ALISTS data for a diverse range of ecology and geomorphology sites
  - Develop acquisition algorithms and enhanced science product generation



# Conclusion



**We successfully accomplished the goals of this IIP by:**

- Developing and demonstrating a highly efficient measurement approach that can meet the LIST mission requirements
- Working with vendor partners, maturing laser and detector technologies needed to achieve the performance requirements
- Designing, assembling, flight testing, and evaluating the Airborne List Simulator, a prototype swath mapping instrument
- Advancing the technical readiness of a scalable instrument architecture for LIST